X-ray microdiffraction applications in integrated circuits

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X-ray Microbeam Instruments

- Microbeam facilities exist in all major synchrotrons.
- Used for:
  - Metrology,
  - Failure analysis,
  - Applied Science.
    - Provide boundary conditions for formulations.
    - Provide test data.

SPring-8 (Super Photon ring-8 GeV)

Industrial Consortium ID (13 companies)	BL16 XU	Undulator	4.5 - 40 keV	X-ray diffraction, X-ray fluorescence analysis and X-ray microbeam analysis for characterization of new industrial materials.
Industrial Consortium BM (13 companies)	BL16 B2	Bending Magnet	3.5 - 60 keV	XAFS and X-ray topography for characterization of new industrial materials.
Hyogo (Hyogo Prefecture)	BL24 XU	Undulator	3.5 - 60 keV	Protein crystal structure analysis. Surface/interface analysis of inorganic materials. X-ray microbeam analysis. X-ray imaging.

ESRF

- **µ-FID-22 :Micro-Fluorescence, Imaging and Diffraction**,
  - **Phase-contrast imaging**
  - **Phase-contrast microtomography**
  - **Micro-topography**
  - **Holography and interferometry**
- ID19 - Topography & Tomography Beamline
- Microfocus beamline ID13
  - Diffraction
  - Small angle x-ray scattering
  - Scanning x-ray microfluorescence

APS

Sector 2: X-ray Microscopy Group

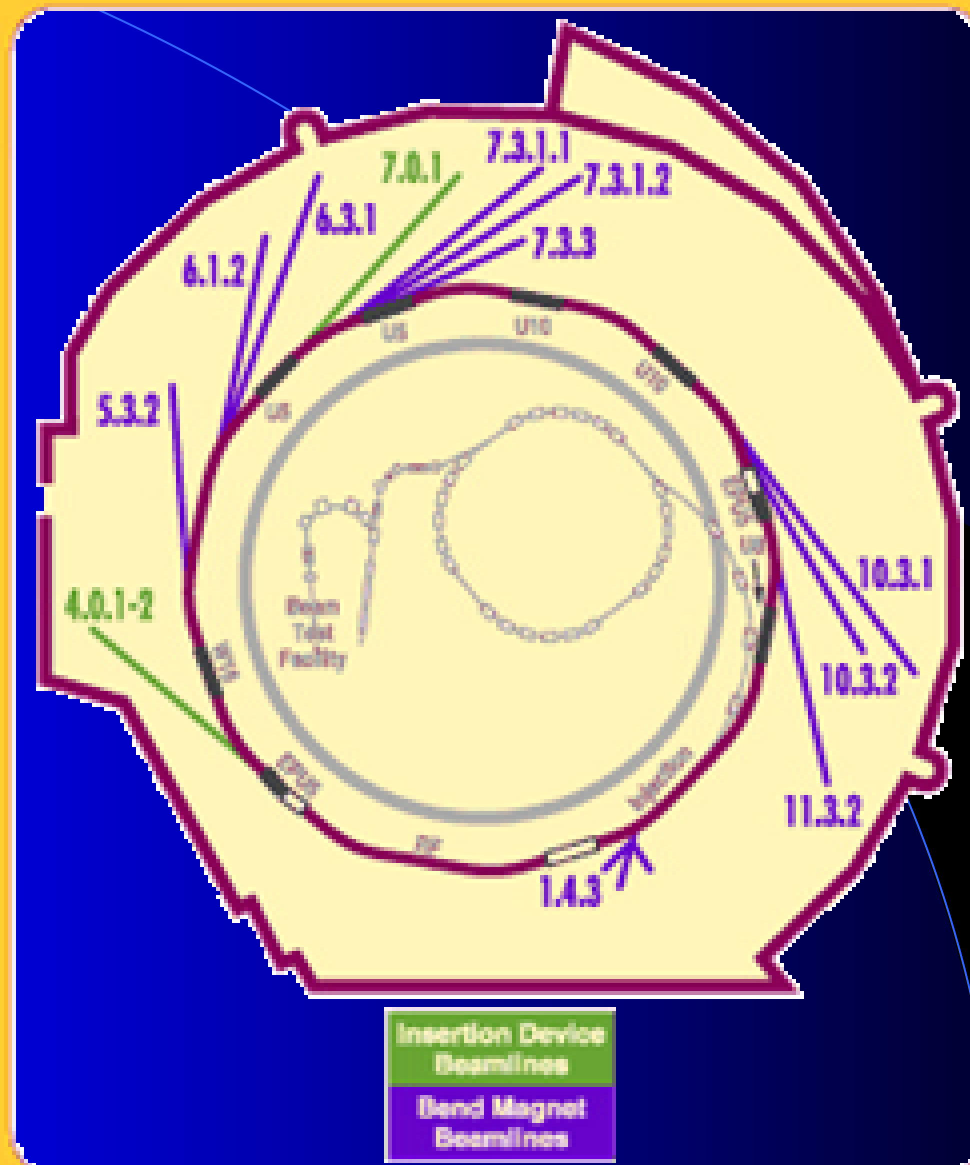
- 2-ID-D : High-resolution fluorescence and diffraction imaging
- 2-ID-E: Sub-micron x-ray fluorescence mapping
- 2-ID-B: High-resolution imaging, coherent scattering.

- MHATT-CAT-Sector7 /UNICAT Beamline 34:
  - Grain by grain strain/texture mapping.
  - Depth resolved mapping.

X-ray nanoprobe beamline; Under development.

Microscopes at the ALS

1.4.3	IR Spectromicroscopy
4.0.1-2	Photoemission Electron Microscopy
5.3.2	Scanning Transmission X-Ray Microscopy for Polymers
6.1.2	Imaging X-Ray Microscopy
6.3.1	MicroESCA
7.0.1	Scanning Photoemission Microscopy, Scanning Transmission X-Ray Microscopy
7.3.1.1	Photoemission Electron Microscopy
7.3.1.2	MicroXPS
7.3.3	Micro X-Ray Diffraction
10.3.1	X-Ray Fluorescence Microprobe
10.3.2	MicroXAS
11.3.2	EUV Lithography Mask Inspection



- CHESS
  - B2 bend magnet station,
  - Tapered capillary optic, Smallest beam: 1000 A diameter @ 6 keV.
- 10^6 photons/sec at the sample @ 12.3 keV
- Microstructure evaluation (Laue photos).

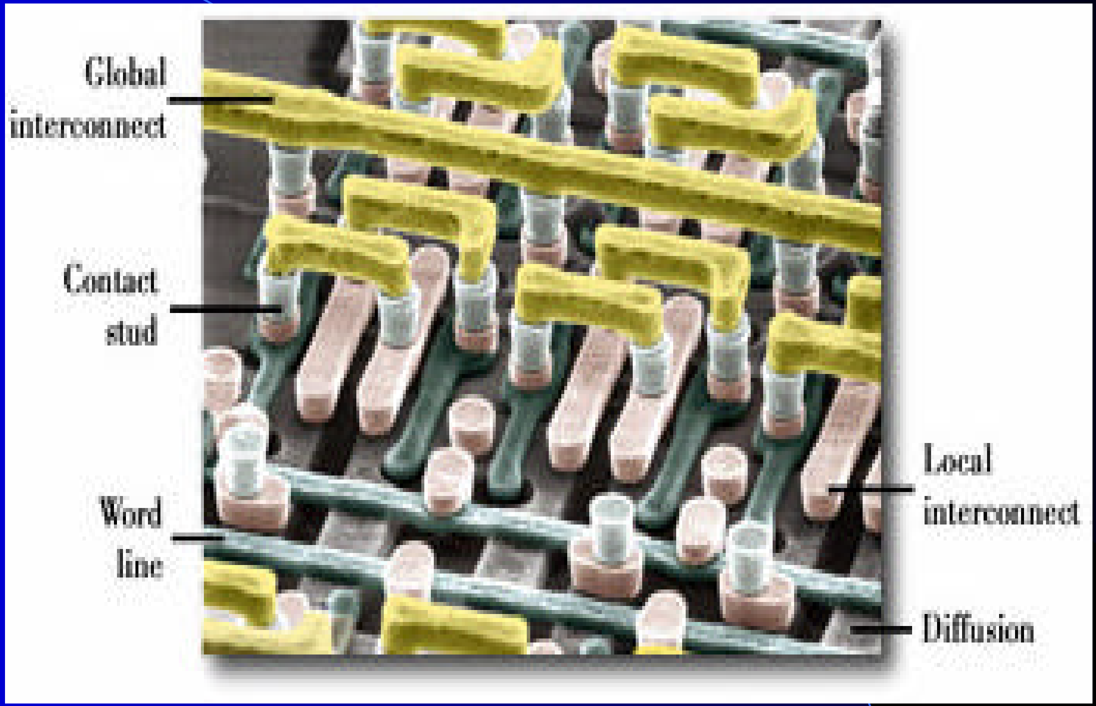
- NSLS
  - X20-IBM
  - X13-B Under construction.

- There are quite exciting machines that are doing microbeam x-ray analysis.
- This is a hot area:
  - ESRF now reports microbeam results as a separate category.
- All have advantages and limitations.
  - Ease of access,
  - Multiple techniques with minimal set-up.
- New rings are being designed with microspot beamlines.

IBM Microdiffraction program

- We are currently investigating:
  - The basic theory of stress/strain analysis in single crystals.
  - Diffraction from strained crystallites.
  - X-ray information volumes.
  - X-ray microbeam metrology.

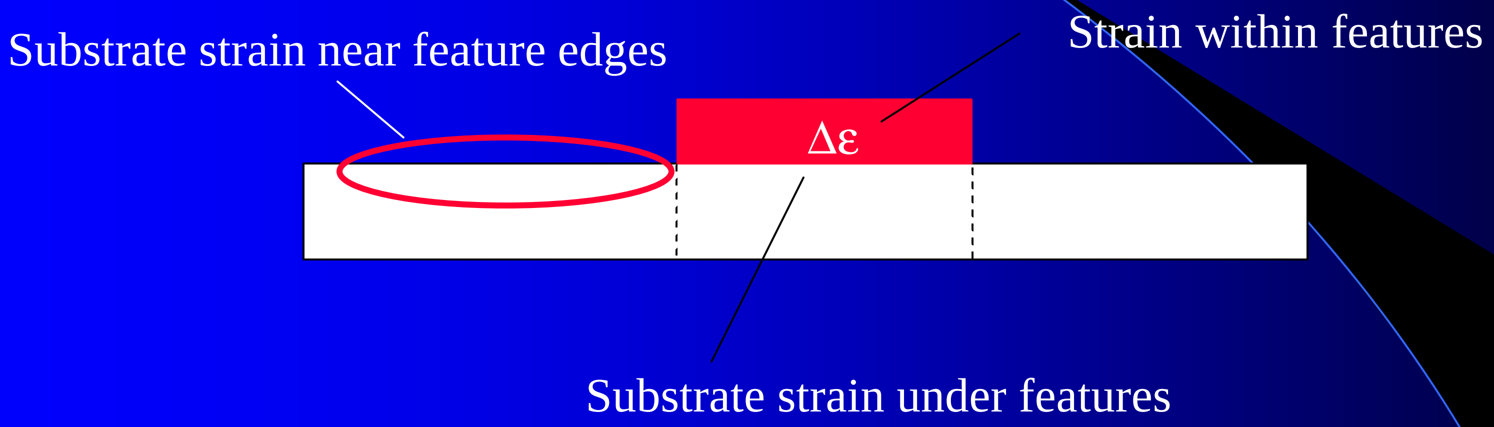
Stresses affect device behavior:
- reliability concerns
-performance issues
    -Faster devices.



Aspects of controlling strain:
- stresses during fabrication
- feature geometry and density
- interfacial integrity

Modeling of mechanical behavior:
-constitutive equations based on bulk behavior
-edge effects dominate stress / strain evolution
➢experimental verification is necessary

Detection of strain by x-ray diffraction



Synchrotron-based x-ray scanning topography:

- dynamic to kinematic transition in substrate diffracted intensity
- highly sensitive to minute strain gradients in single crystal substrates

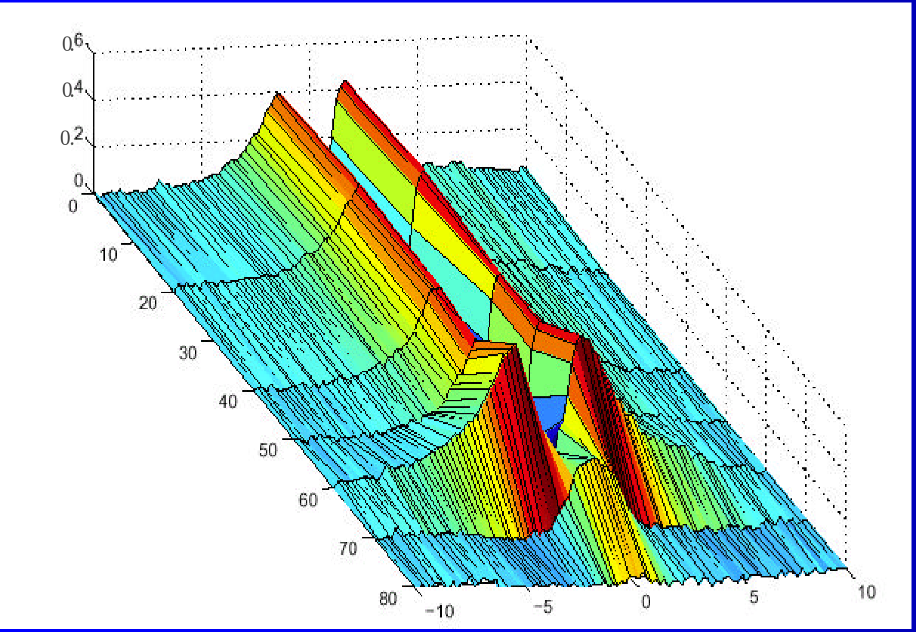
Measurements

Conducted at APS 2ID-D

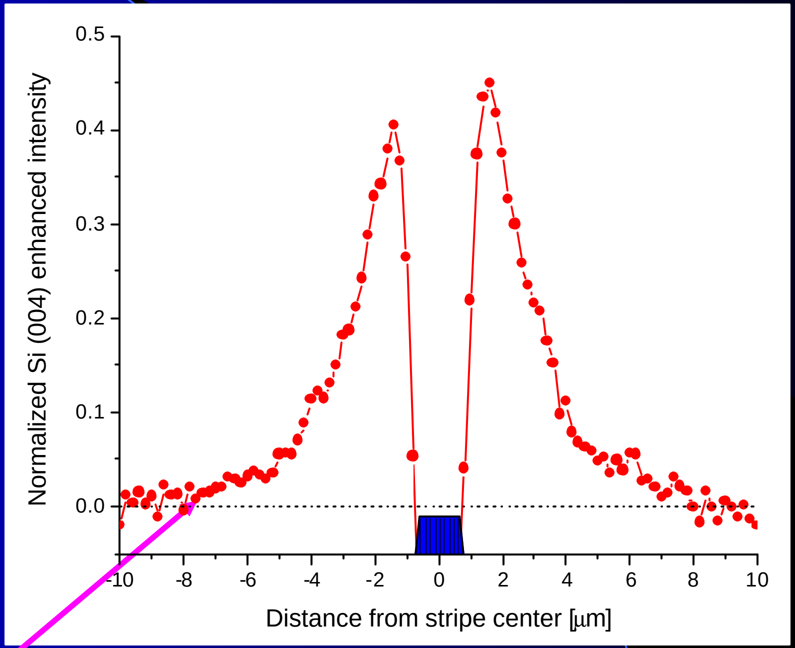
- UHV/CVD 0.24 μm thick $Si_{0.86}Ge_{0.14}$ on Si (001)
- 100 μm features etched (various widths)
- Fresnel zone plate optics, beam size ~ 0.3 μm
- E = 9.2 keV
- Map Si (004) and SiGe (004) diffracted intensity

Experimental: 1.5 μm SiGe feature on Si (001)

Normalized Si diffracted intensity [$\Delta I/I_0$]



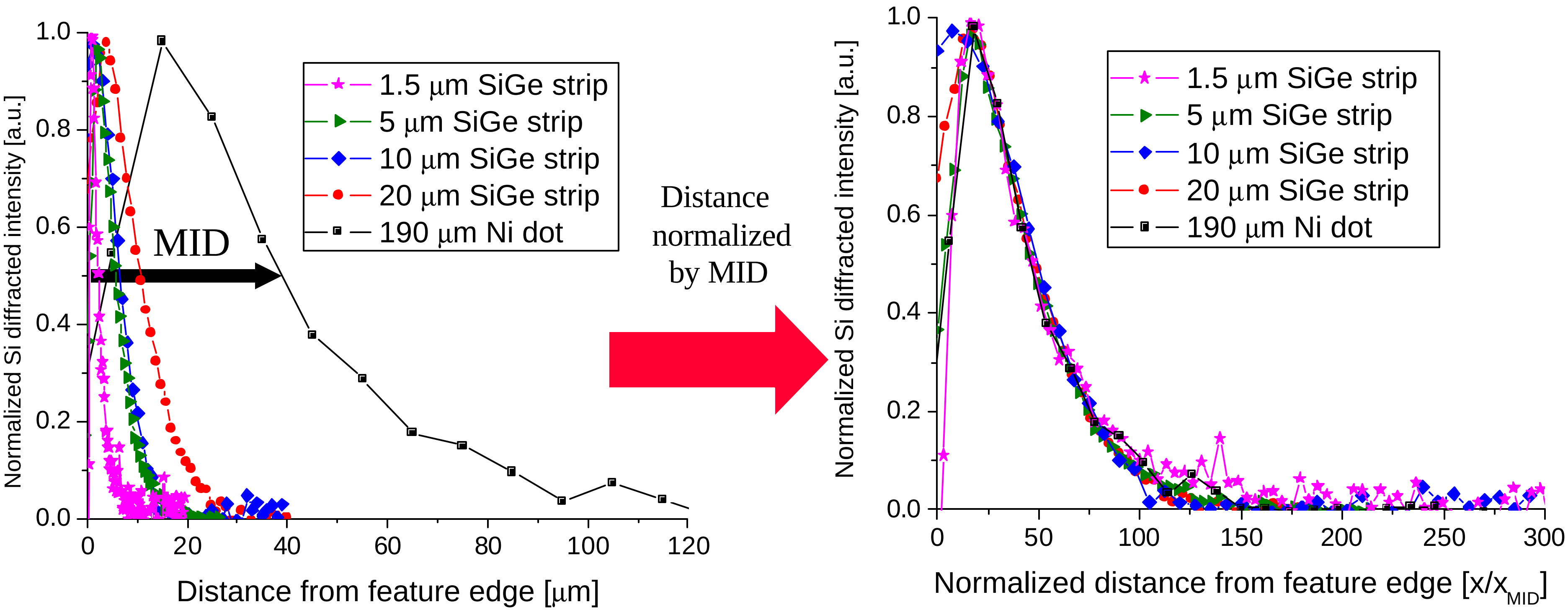
Distance from stripe center [μm]



- Distortion in Si substrate detected ~ 7 μm away from stripe edge (30 x/t)
  - The smaller the beam size, the better the resolution.
  - The 0.3 micron beam size is very important.

Comparison of distortion fields in Si

- Extent of deformation in Si: 7 μm to 30 μm from SiGe feature edge

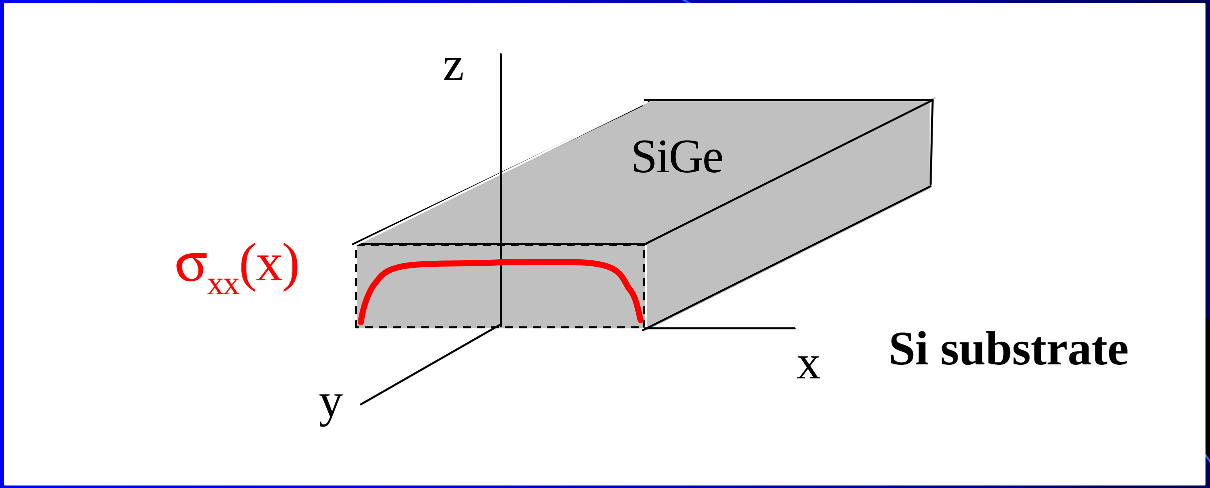


Decay of magnitude of strain follows characteristic curve:

➢ NOT predicted by traditional mechanical models (analytical, FEM)

C.E. Murray et al., Appl. Phys. Lett. **83**, 4163 (2003)

Elastic relaxation due to edge effects



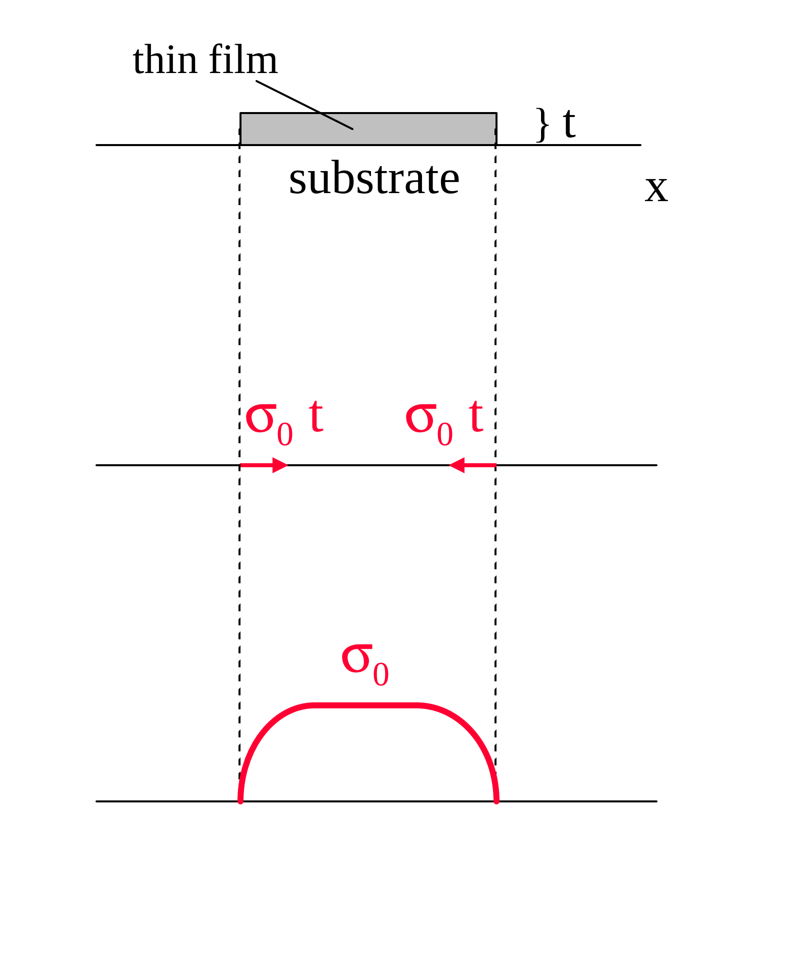
Free surfaces cannot support normal stress ($\sigma_{xx}\, n_x = 0$)

- assess the effect of feature width on in-plane normal stress (σ_{xx})

Measure out-of-plane lattice deformation to determine in-plane stress

- assume $\sigma_{zz} = 0$, $\sigma_{yy} = \sigma_0$ (stress in blanket film)

Mechanical modeling



Elastic half-space solutions

- substrate is semi-infinite

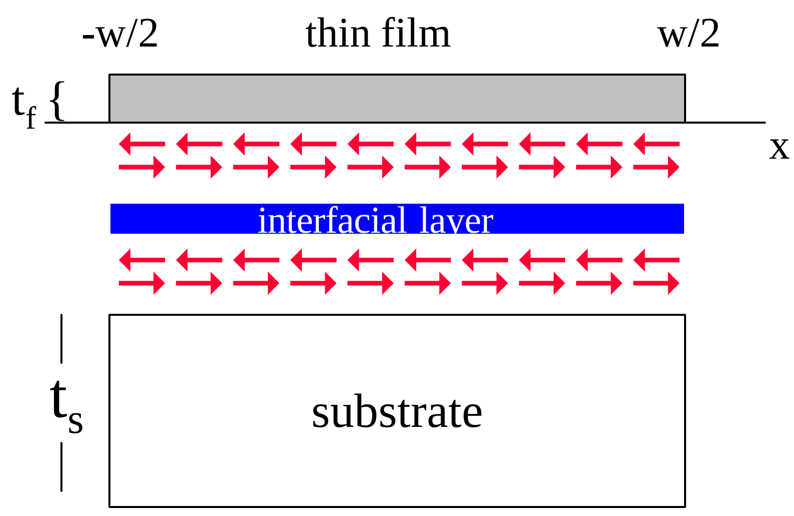
Edge-force model

- Blech and Meieran (based on Love)
- interaction at film edges

Distributed-force model

- Hu
- decay in normal stress dictated by compatibility at interface

Mechanical modeling (cont.)



$$t(x)=\left(\frac{G_{int}}{t_{int}}\right)\left[u_{film}(x)-u_{sub}(x)\right]$$

Finite-thickness formulations

- elastic load transfer through shear across interface
- film and substrate possess equal widths (w)

Lap shear

- Suhir
- eigenvalue, $K = f(E_i, t_i)$

Shear Lag

- Chen and Nelson
- shear is controlled by interfacial compliance parameter (G_{int}/t_{int})

As feature width becomes infinite (w →8), results asymptote to Timoshenko model

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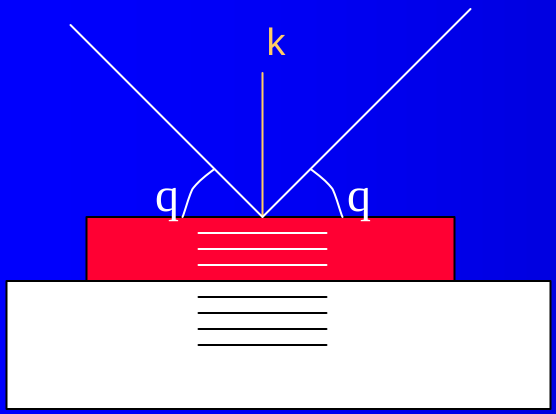
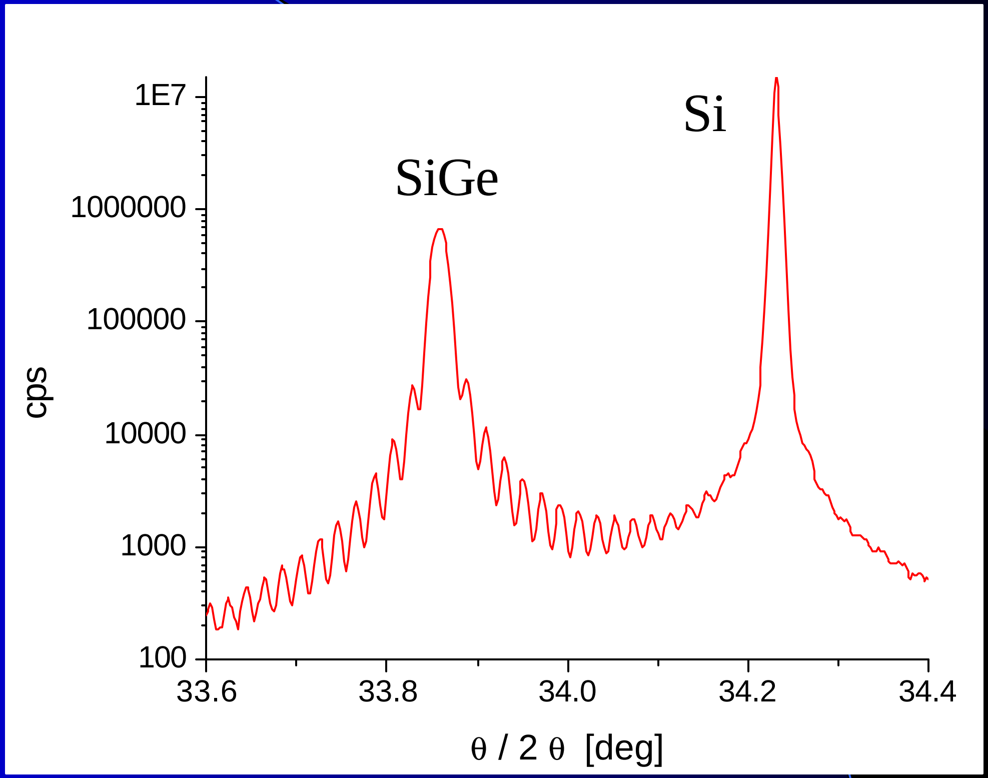
Measurements

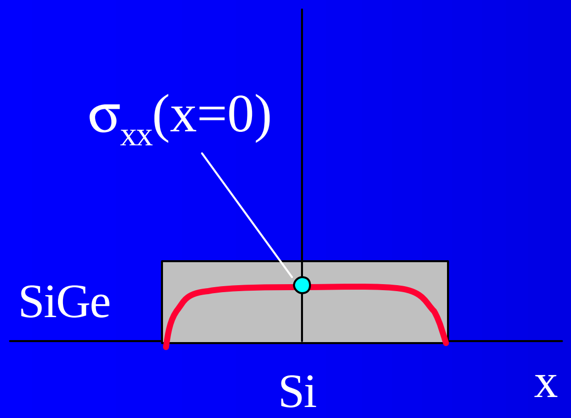
- θ / 2θ scans at feature centers
- Difference in Si (004) and SiGe (004) peak position
  - out-of-plane SiGe strain
  - normal stress at feature center

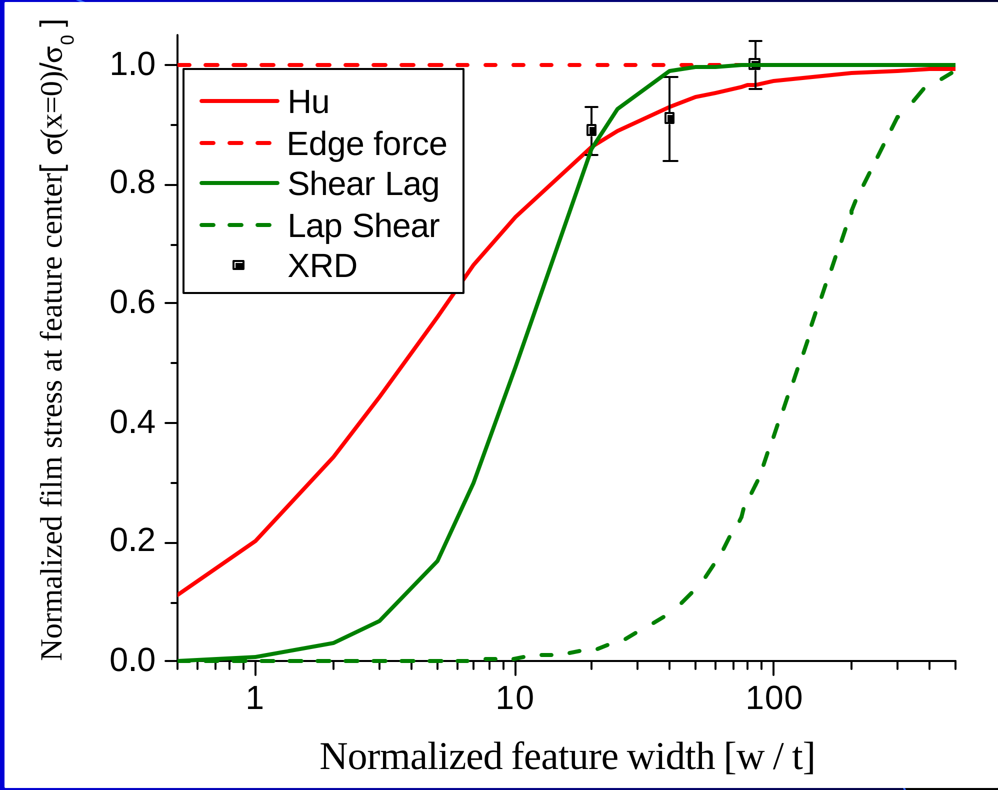


blanket SiGe prior to etching



Comparison of stress measurements to models



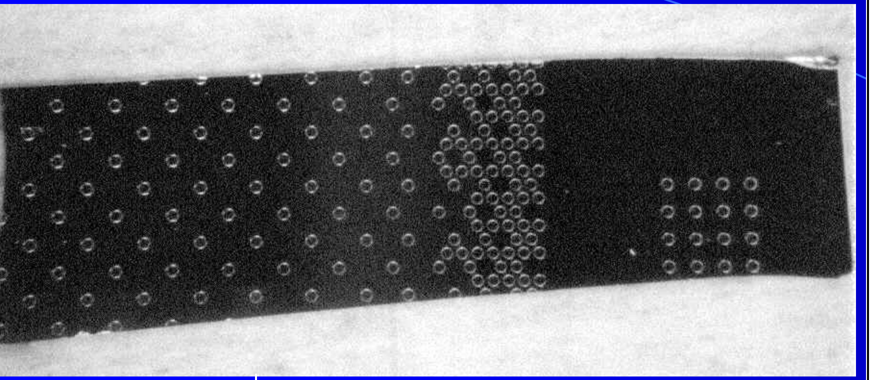


- Elastic relaxation in SiGe features on Si due to edge effects:
  - close to Hu and shear lag approximations

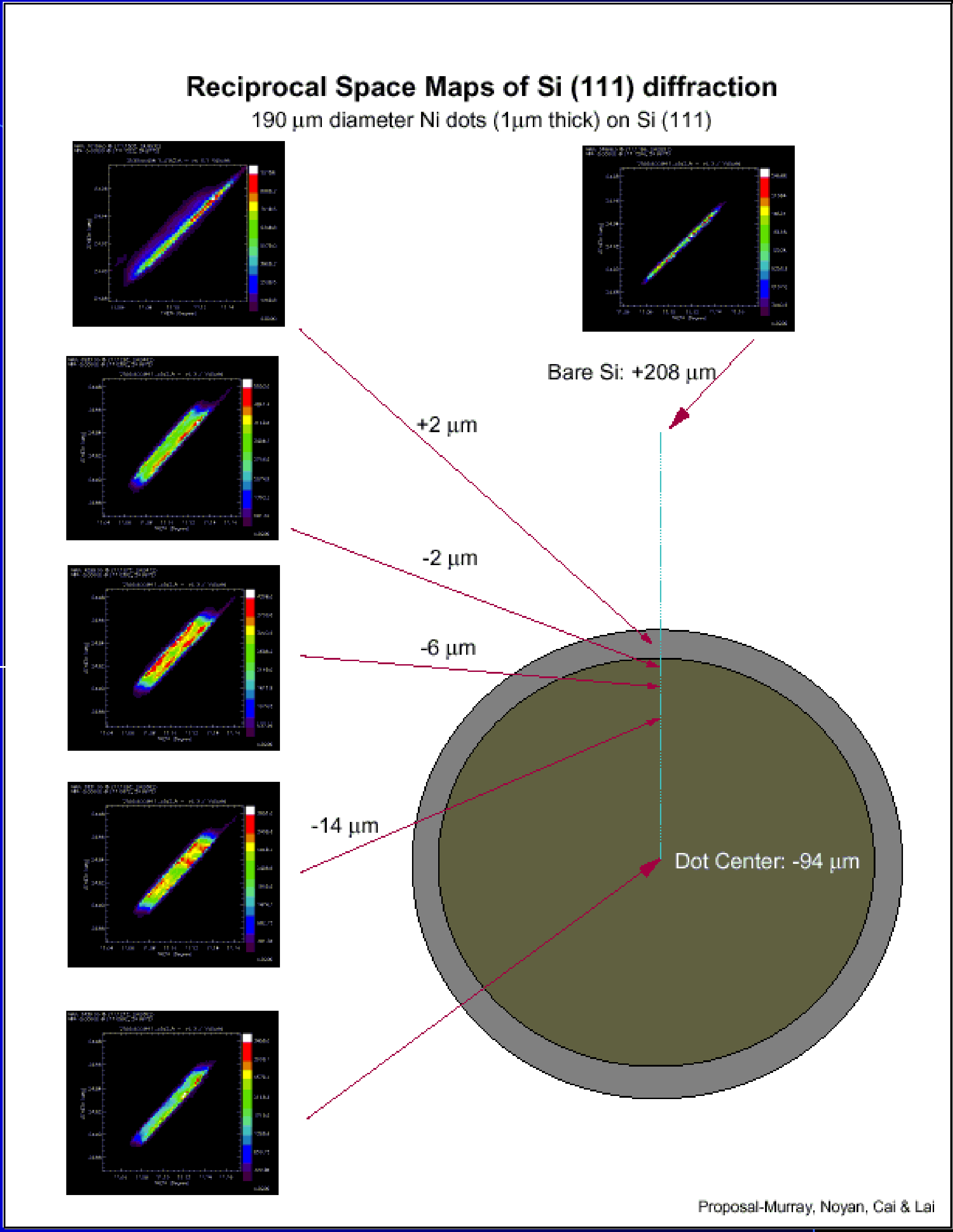
- More comprehensive models are being developed to incorporate:
  - out-of-plane elastic relaxation
  - observed strain decay in substrate outside of feature

High-Resolution Microdiffraction

- Full reciprocal space mapping of single-crystal reflections.
- Necessary to resolve the epitaxial strain effects.
- Requires a parallel beam and analyzer crystal.
- Requires some optical advances.



Optical micrograph.



We observe the formation of a second peak.

We also observe some Kiessig fringes.

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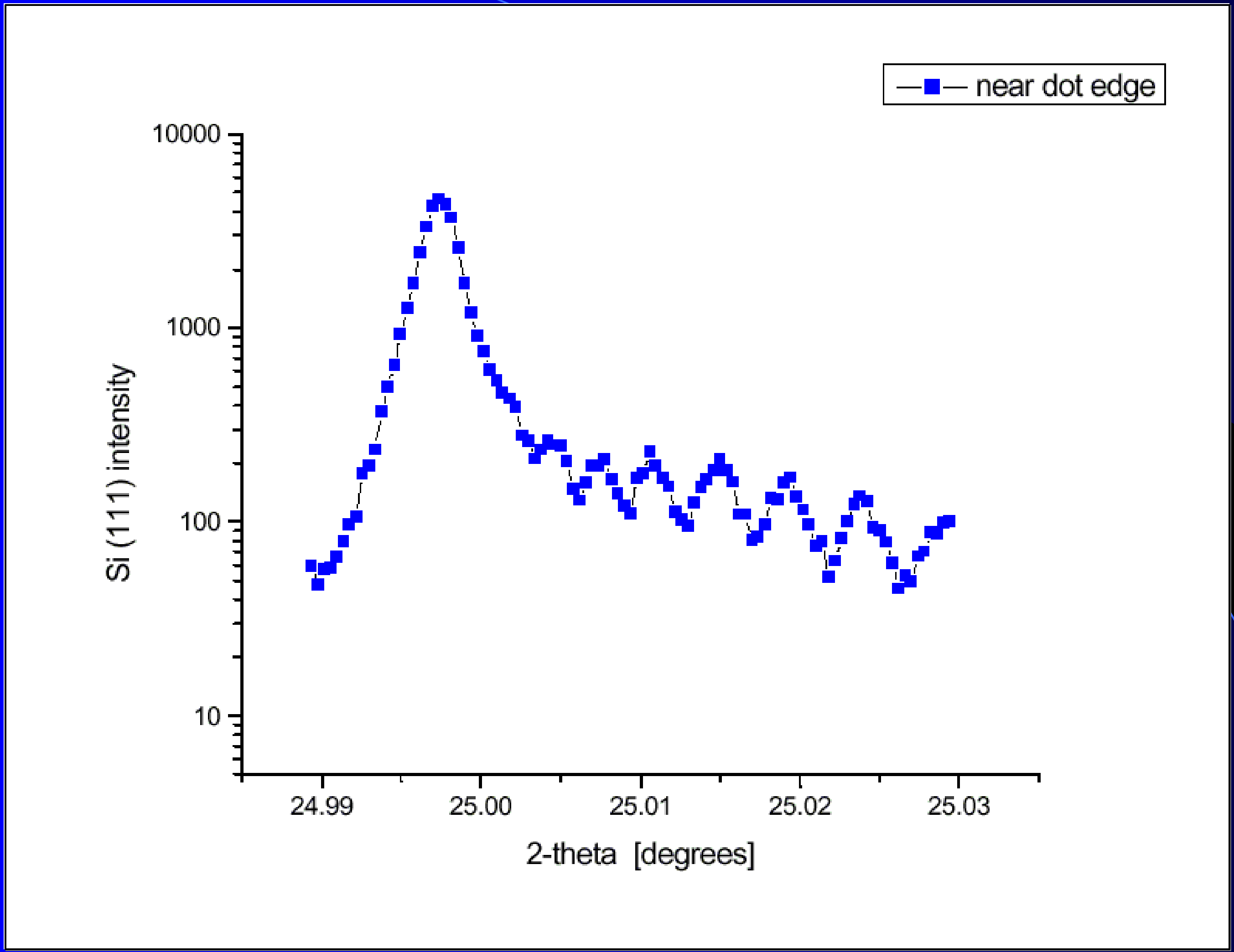


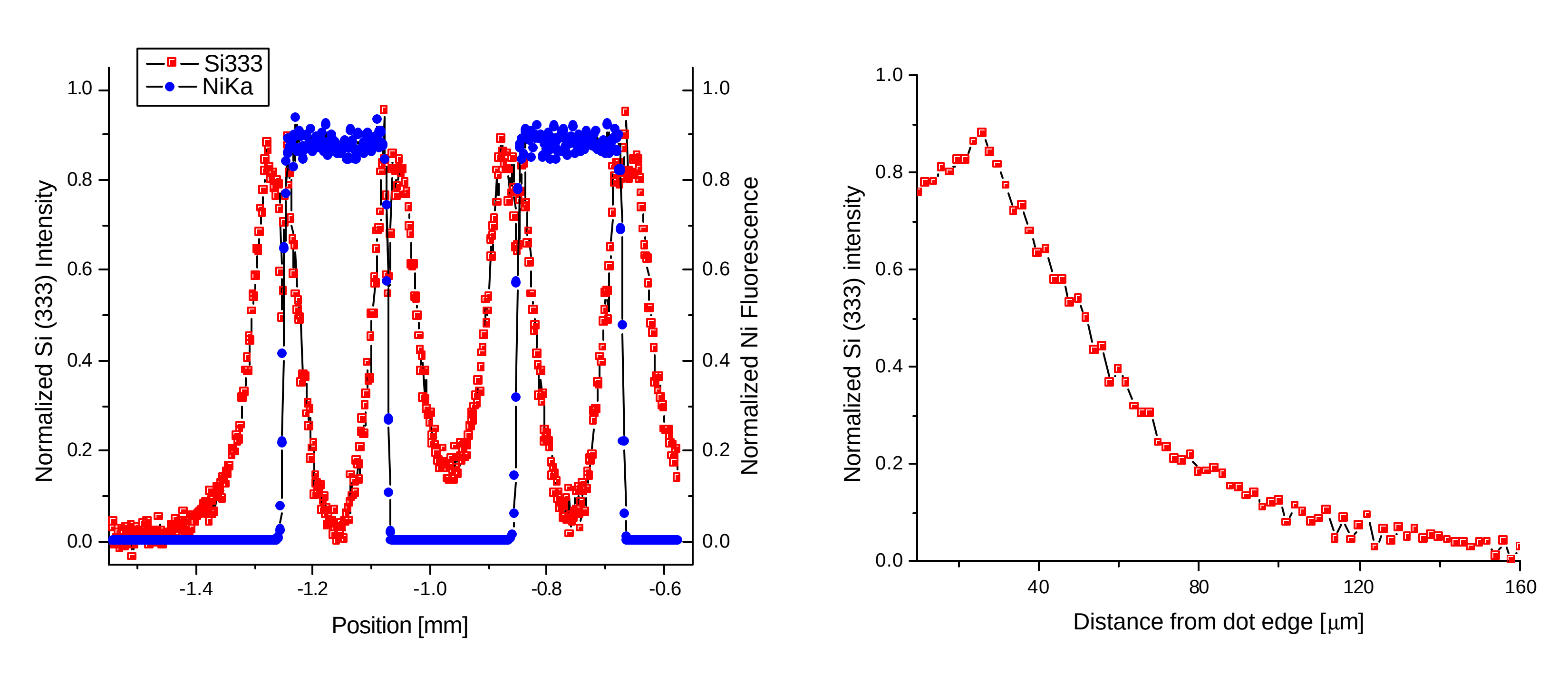
near dot edge
10000
1000
100
10
Si (111) intensity
24.99
25.00
25.01
25.02
25.03
2-theta [degrees]

Summary and future work

- X-ray microbeam measurements reveal strain in thin film / substrate systems
- Extent of strain fields in substrate
  - more than 100 times feature thickness away from edge
  - not predicted by current mechanical models
    - dynamic diffraction (H. Yan)
- Edge effects in thin film features
  - elastic relaxation measured in SiGe stripes
- Mechanical modeling implemented to describe observed behavior
    - analytical, FEM (S. Polvino)

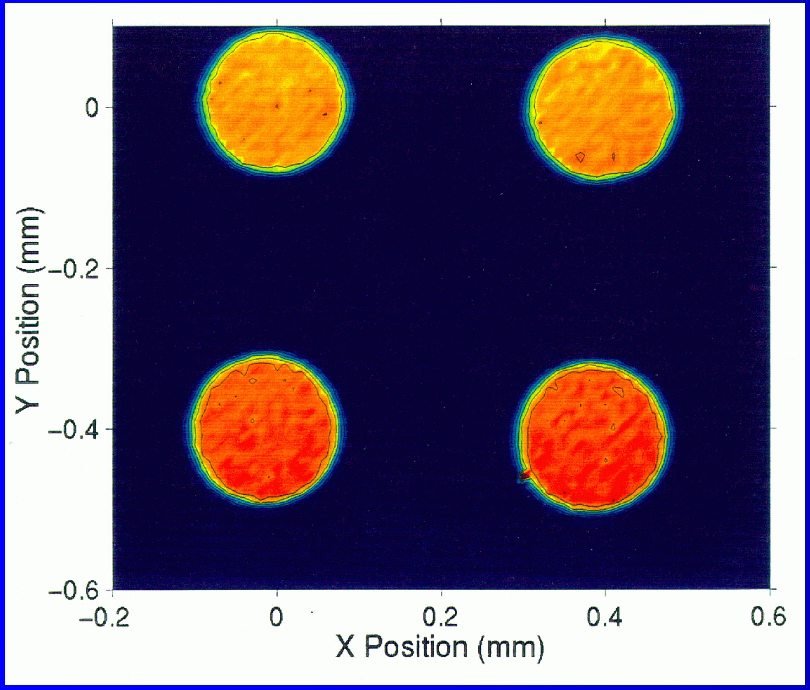
Enhanced Si (333) intensity

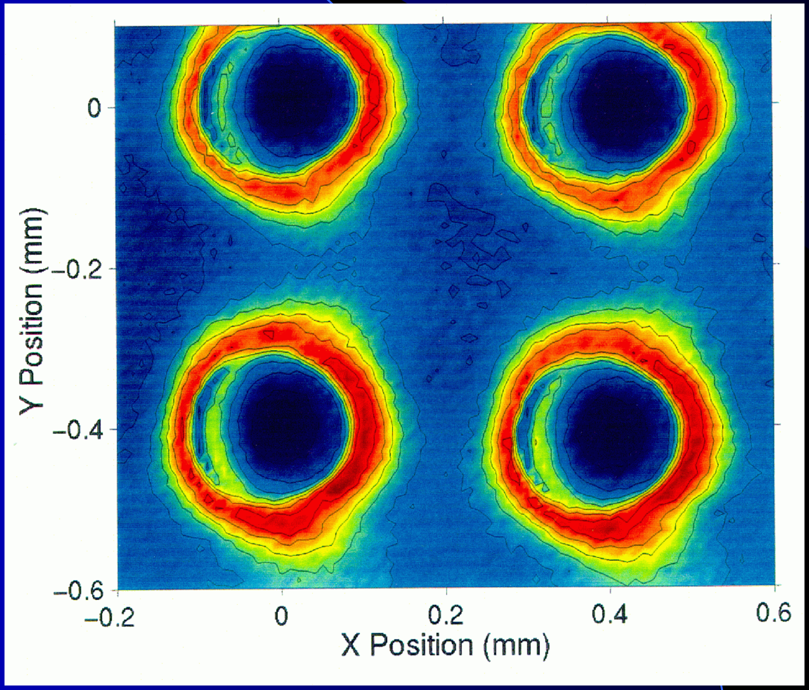
- Line scans of Si (333) vs. position confirm diffracted intensity increase due to strain
- Effects of Ni dot observed in Si substrate approximately 120 μm away



Enhanced x-ray diffraction

- Maps of Ni Kα fluorescence and Si (333) diffraction
  - effects of strain on dynamic to kinematic transition in Si single crystal substrate





From Noyan et al., APL **74**, 2352 (1999)

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